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Spatiotemporal variations in ecosystem services and their trade-offs and synergies against the background of the gully control and land consolidation project on the Loess Plateau, China

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Abstract: Studying the spatiotemporal variations in ecosystem services and their interrelationships on the Loess Plateau against the background of the gully control and land consolidation (GCLC) project has significant implications for ecological protection and quality development of the Yellow River Basin. Therefore, in this study, we took Yan'an City, Shaanxi Province of China, as the study area, selected four typical ecosystem services, including soil conservation service, water yield service, carbon storage service, and habitat quality service, and quantitatively evaluated the spatiotemporal variation characteristics and trade-offs and synergies of ecosystem services from 2010 to 2018 using the Integrated Valuation of Ecosystem Services and Trade-offs (InVEST) model. We also analysed the relationship between the GCLC project and regional ecosystem service changes in various regions (including 1 city, 2 districts, and 10 counties) of Yan'an City and proposed a coordinated development strategy between the GCLC project and the ecological environment. The results showed that, from 2010 to 2018, soil conservation service decreased by 7.76%, while the other three ecosystem services changed relatively little, with water yield service increasing by 0.56% and carbon storage service and habitat quality service decreasing by 0.16% and 0.14%, respectively. The ecological environment of Yan'an City developed in a balanced way between 2010 and 2018, and the four ecosystem services showed synergistic relationships, among which the synergistic relationships between soil conservation service and water yield service and between carbon storage service and habitat quality service were significant. The GCLC project had a negative impact on the ecosystem services of Yan'an City, and the impact on carbon storage service was more significant. This study provides a theoretical basis for the scientific evaluation of the ecological benefits of the GCLC project and the realization of a win-win situation between food security and ecological security.

Keywords: ecosystem services; trade-offs and synergies; gully control and land consolidation; habitat quality; Integrated Valuation of Ecosystem Services and Trade-offs (InVEST) model; Loess Plateau

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1 Introduction

Ecosystem services refer to the biological resources, natural environment conditions, and utility provided for human survival through ecosystems and ecological processes (Costanza et al., 1997). The assessment of ecosystem service value measures the ecological benefits to humans based on the change in ecosystem services in a certain period of time, which can quantitatively and intuitively capture the impact of ecological governance measures on the ecological environment in a region (Ouyang and Wang, 2000). Due to the diversity and complexity of ecosystem services, they usually show trade-offs or synergies of simultaneous enhancement and weakening (Maskell et al., 2013). Studying the spatiotemporal evolution of various ecosystem services and identifying trade-offs and synergies among them can analyze and evaluate the impact of trade-offs on human welfare and maximize the benefits of various ecosystem services. It is of great significance for regional development, ecological protection, and the formulation of ecological policies.

The development of 3S technology, including Geographic Information System (GIS), Remote Sensing (RS), and Global Positioning System (GPS), has allowed evaluation model to be increasingly applied to ecosystem service evaluation due to its advantages in spatial analysis, data acquisition, assessment accuracy, and dynamics. The Integrated Valuation of Ecosystem Services and Trade-offs (InVEST) model has a number of modules that simulate the material benefits or value of ecosystem services under different land use types. It is widely used in the dynamic assessment and spatiotemporal change analysis of ecosystem services. Turner et al. (2014) studied the spatial distribution and interaction of 11 ecosystem services in Denmark and analysed the relationship between ecosystem services and cultural landscape of the country. Clerici et al. (2019) revealed the effects of climate change and land use types on the spatiotemporal pattern of ecosystem services in Kentucky and two small basins in the eastern Andes Mountains in the United States by setting different scenarios. In China, Cao et al. (2021), Gao et al. (2021), and Jing et al. (2022) used models to evaluate and simulate ecosystem service functions at various scales in Beijing City, Nagqu City of Tibet Autonomous Region, and Wolong Nature Reserve of Sichuan Province, respectively, and analyzed the trade-offs among various ecosystem services.

The Loess Plateau is located in the middle of the Yellow River Basin, which is a fragile ecological environment area with a prominent conflict between people and land. It plays a very important role in ecological protection and high-quality development strategy of the Yellow River Basin. Yan'an City is the most representative city on the Loess Plateau. As the key demonstration area of the largest ecological environment construction project in China in the 21st century, the Grain for Green (GFG) project, the ecological environment of Yan'an City has been significantly improved during the period of the GFG project (He, 2015; Han et al., 2021). However, with the further progress of the project, problems such as cultivated land reduction and food security crisis have arisen (Zhou and An, 2014; He et al., 2015). With the development of the city and the rise of red tourism, population growth and urbanization development have increased the demand for cultivated land. Therefore, in view of the special geomorphology in the hilly and gully region of the Loess Plateau, in order to increase the cultivated land area and ensure food security, local government and researchers carried out the gully control and land consolidation (GCLC) project in Yan'an City, which is a new management model that includes dam system construction, old dam restoration, saline-alkali land transformation, development and utilization of waste and unused land, and ecological construction (He, 2015).

In terms of the impact of land consolidation on the ecosystem, some scholars have argued that land consolidation in Yan'an City will destroy the water system and ecosystem (Li et al., 2014; Jin et al., 2019), but other studies have shown that the project has a positive impact on the ecosystem. The GCLC project can significantly increase regional vegetation cover, improve the ecological environment (He et al., 2020), and promote the benign evolution of regional ecosystems (Li et al., 2019). Both the ecological capacity value and the area of arable land have increased due to land-use management, suggesting that this project has a positive effect on the study area (Chen et al., 2020).

Previous studies on the environmental impact of projects have basically been carried out at the project scale. How do the regional ecosystem services change before and after the implementation of the GCLC project? Is there a trade-off or a synergistic relationship between each ecosystem service? Is there any correlation between the GCLC project and ecosystem service changes? These questions are unclear. Therefore, taking Yan'an City as the study area and before and after the project as the study period, in this study, we selected four typical ecosystem services, including soil conservation service, water yield service, carbon storage service, and habitat quality service, and quantitatively analyzed the spatiotemporal distribution and variation characteristics of regional ecosystem services from 2010 to 2018 by using the InVEST model and ArcGIS software. We revealed the trade-off and synergistic relationships, and analyzed the relationship between the GCLC project and regional ecosystem service changes to provide a scientific basis and decision-making support for the ecological benefit evaluation of the GCLC project and ecological protection and quality development of the Loess Plateau, China.

2 Materials and methods

2.1 Study area

Yan'an City (35°20′39″–37°53′31″N, 107°38′59″–110°34′46″E) is located in the hinterland of the Loess Plateau, in the middle reaches of the Yellow River, and is 256 km wide from east to west and 236 km long from south to north. It is characterized by a semi-humid and semi-arid continental monsoon climate, with cold and dry winters and hot and rainy summers. The average annual precipitation is 562 mm and is relatively concentrated in summer (July to September). The annual average temperature is 9°C, and the average frost-free period is 179 d. Yan'an City is a loess hilly and gully region, with high terrain in the northwest and low terrain in the southeast (Fig. 1). The north is dominated by loess hills and gullies, accounting for 72.00% of the total area. The south is dominated by loess plateau gullies, accounting for 19.00% of the total area, and stone mountains account for 9.00% of the total area. The main feature of the river system distribution in Yan'an City is a deep trunk with dense branches. The terrain in the area is fragmented, with various gullies and ravines. The gully is strongly cut down by a large slope and serious soil erosion. Yan'an City has 1 city (Zichang City), 2 districts (Baota District and Ansai District), and 10 counties (including Yanchang County, Yanchuan County, Zhidan County, Wuqi County, Ganquan County, Fuxian County, Luochuan County, Yichuan County, Huanglong County, and Huangling County), with a total population of 2.19 million.

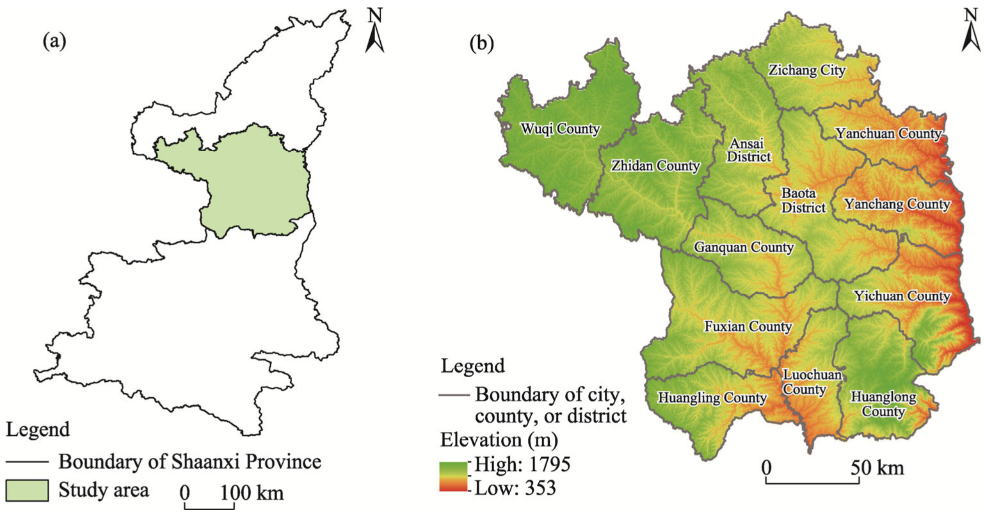

Fig. 1 Location (a) and elevation (b) of the study area. Note that the boundaries of province, city, county, and district are derived from the Resource and Environmental Sciences and Data Center, Chinese Academy of Sciences (http://www.resdc.cn).

The GCLC project of Yan'an City was first piloted in Baota District, Zichang City, and Yanchuan County in 2010. In September 2012, it was listed as a major national land consolidation project and given support. In November 2013, it was officially approved (Zhang and Jin, 2015). The GCLC project involved 13 regions (including 1 city, 2 districts, and 10 counties) of the city, with a total of 197 sub-projects, which were implemented intensively from 2013 to 2017. The construction scale was 36,986.22 hm^2, the newly increased cultivated land was 7848.72 hm^2, and the high-standard farmland was 28,233.29 hm^2, with an investment of 366,407.68×10^4 CNY (Table 1). At the same time, the GFG project in Yan'an City entered the consolidation stage in 2010. The forest cover in the city reached 36.6%, and the regional ecological environment was greatly restored. In 2013, Yan'an City carried out a new round of the GFG project, planning to gradually return all sloping farmland above 25° to forest and achieve full afforestation of steep slopes and full forest and grass cover.

Table 1 Implementation scale of the gully control and land consolidation (GCLC) project in different regions of Yan'an City

Region	Number of projects	Construction scale (hm^2)	Newly increased cultivated land (hm^2)	High-standard farmland (hm^2)	Investment amount (×10^4 CNY)
Baota District	34	7734.74	1190.80	6183.23	80,892.24
Yanchang County	16	3403.09	831.10	2698.84	34,277.77
Yanchuan County	14	3561.59	801.65	2795.02	38,754.82
Zichang City	29	4919.54	817.47	3214.24	50,370.23
Ansai District	20	2405.95	631.72	1910.32	21,229.54
Zhidan County	3	330.95	95.94	134.13	3375.71
Wuqi County	10	2159.59	838.22	1244.78	19,880.75
Ganquan County	19	3278.88	529.10	2625.58	30,824.60
Fuxian County	16	3070.66	428.47	2460.37	28,438.50
Luochuan County	13	2191.04	616.59	1782.51	22,917.90
Yichuan County	8	1873.35	611.62	1423.52	16,289.26
Huanglong County	7	820.93	157.38	707.20	7518.75
Huangling County	8	1235.91	297.66	1053.55	11,637.61
Total	197	36,986.22	7847.72	28,233.29	366,407.68

2.2 Data sources

The basic data used in this study include land use data, elevation data, meteorological data, soil data, and data from the GCLC project. The land use data in 2010 and 2018 were obtained from the Resource and Environmental Sciences and Data Center, Chinese Academy of Sciences (http://www.resdc.cn), with a spatial resolution of 30 m. According to the land use/cover change classification system established by Liu (1997), land use types were divided into 6 primary classifications and 18 secondary classifications. Elevation data were obtained from the Geospatial Data Cloud (http://www.gscloud.cn) with a spatial resolution of 30 m. In order to extract the vector map of sub-basins, we used the digital elevation model (DEM) to calculate the flow direction and the cumulative amount of convergence and other operations in ArcGIS. Meteorological data were obtained from the National Scientific Data Center for the Tibetan Plateau-1-km monthly precipitation dataset for China (1901–2020) (https://data.tpdc.ac.cn), with a spatial resolution of 1 km. The soil data were from the Harmonized World Soil Database (HWSD) soil dataset (v.1.2) of the National Scientific Data Center for the Tibetan Plateau (https://data.tpdc.ac.cn), which included soil texture, soil organic carbon content, vegetation available water content, root depth, and other data, with a spatial resolution of 1 km. The data of the GCLC project are from the completion and acceptance files of 197 land consolidation projects.

2.3 Research methods

According to the classification system of ecosystem services proposed by the United Nations Millennium Ecosystem Assessment (MEA, 2005) and combined with the ecological environment characteristics of Yan'an City, we screened four main ecosystem service types, including soil conservation service, water yield service, carbon storage service, and habitat quality service, to evaluate the ecosystem services before and after the GCLC project in Yan'an City.

2.3.1 Soil conservation service

We used the SDR (sediment transport ratio) module of the InVEST model to calculate potential soil erosion based on terrain, climate, and soil data and actual soil erosion based on the cover-management factor and soil and water conservation factor. The difference between the two is the soil conservation amount on the raster unit. The calculation formulas are as follows:

$$RKLS_i = R_i \times K_i \times LS_i \,, \tag{1}$$

$$USLE_i = R_i \times K_i \times LS_i \times C_i \times P_i \,, \tag{2}$$

$$SR_i = RKLS_i - USLE_i \,, \tag{3}$$

where $RKLS_i$ is the potential soil erosion of pixel i (t/hm^2); $USLE_i$ is the soil erosion amount of pixel i under the action of cover-management factors and soil and water conservation factors (t/hm^2); SR_i is the actual soil conservation of pixel i (t/hm^2); R_i is the rainfall erosivity factor, calculated by Wischmeier's empirical formula (Wischmeier and Smith, 1958), and ANUSPLIN4.2 software is used for spatial interpolation; K_i is the soil erodibility factor, calculated by erosion-productivity impact calculator model (Williams, 1990), the calculated results were assigned to different soil types, and the grid size was set as 30 m×30 m; LS_i is the slope length-gradient factor, which is calculated from DEM data; C_i is the cover-management factor; and P_i is the soil and water conservation factor.

2.3.2 Water yield service

Based on the principle of water cycle, we used the water conservation module of the InVEST model to obtain water yield by calculating parameters such as precipitation, plant transpiration, surface evaporation, root depth, and soil depth. The calculation formulas are as follows:

$$Y_{xj} = P_x \times \left(1 - \frac{AET_{xj}}{P_x}\right), \tag{4}$$

$$\frac{AET_{xj}}{P_x} = \frac{1 + \omega_x R_{xj}}{1 + \omega_x R_{xj} + \dfrac{1}{R_{xj}}}, \tag{5}$$

$$\omega_x = Z \times \frac{AWC_x}{P_x} + 1.25 \,, \tag{6}$$

$$AWC_x = \min(\max \mathrm{SoilDep}_{thx}, \mathrm{RootDep}_{thx}) \times PAWC_x \,, \tag{7}$$

$$\begin{aligned} PAWC_x = {} & 54.509 - 0.132 \times \mathrm{SAN} - 0.003 \times \mathrm{SAN}^2 - 0.055 \times \mathrm{SIL} - 0.006 \\ & \times \mathrm{SIL}^2 - 0.738 \times \mathrm{CLA} + 0.007 \times \mathrm{CLA}^2 - 2.688 \times \mathrm{OC} + 0.501 \times \mathrm{OC}^2 \end{aligned}, \tag{8}$$

$$R_{xj} = \frac{k_{xj} \times ET_{0x}}{P_x}, \tag{9}$$

$$ET_{0x} = 0.0013 \times 0.408 \times RA \times (T_{\mathrm{avg}} + 17.8) \times (TD - 0.0123 P_x)^{0.76}, \tag{10}$$

where Y_{xj} is the annual water yield in pixel x of land use type j (mm); P_x is the annual precipitation in pixel x (mm); and AET_{xj} is the annual actual evapotranspiration in pixel x (mm); ω_x is the ratio of annual water requirement to annual precipitation on vegetation; R_{xj} is the Budyko dryness index in pixel x of land use type j and represents the ratio of potential evaporation to precipitation; Z is the seasonal constant between 0 and 30; AWC_x is the volumetric

plant available water content (mm); $SoilDep_{thx}$ is the soil root depth (mm); $RootDep_{thx}$ is the plant root depth (mm); $PAWC_x$ is the plant available water content (%); SAN, SIL, CLA, and OC are the contents of sand (%), silt (%), clay (%), and organic carbon (%), respectively; k_{xj} is the evapotranspiration coefficient of vegetation, representing the ratio of vegetation evapotranspiration to the potential evapotranspiration (ET_{0x}) at different vegetation growth stages; RA is the radiation from the top layer of the atmosphere (MJ/(m^2•d)); T_{avg} is the average of the mean daily maximum temperature and the mean daily minimum temperature (°C); and TD is the difference between the mean daily maximum temperature and the mean daily minimum temperature (°C).

2.3.3 Carbon storage service

Ecosystems store carbon in plants, soil, or other biomass. We used the carbon module of the InVEST model to evaluate regional ecosystem carbon stocks according to each land use type and corresponding carbon density data. The model divided the carbon storage in the ecosystem into four basic carbon pools: all living plants above the soil (aboveground biomass), living plant roots (underground biomass), soil organic matter, and dead organic matter. Since the carbon density of dead organic matter is small and the data are difficult to obtain, it is not considered in this study. The basic equation for carbon stock is as follows:

$$\mathrm{C}=\mathrm{C}_{\text{above}}+\mathrm{C}_{\text{below}}+\mathrm{C}_{\text{soil}}\,, \tag{11}$$

where C is the total carbon density of the ecosystem (t/hm^2); and C_{above}, C_{below}, and C_{soil} are aboveground carbon density (t/hm^2), belowground carbon density (t/hm^2), and soil carbon density (t/hm^2), respectively.

2.3.4 Habitat quality service

Habitat quality is an indicator that connects biodiversity and different land use types. We used the habitat quality module of the InVEST model to calculate habitat quality service by using the relative impact of the threat of each land use type, the relative sensitivity of the habitat type to each threat, and the distance between the habitat raster and the threat source. Habitat quality values ranged from 0 to 1, with higher values indicating better habitat quality. Habitat quality was calculated using the following formulas:

$$D_{xj}=\sum_{r=1}^{R}\sum_{y=1}^{Y_r}\left(\frac{W_r}{\sum_{r=1}^{R}W_r}\right)r_y i_{rxy}\beta_x S_{jr}\quad , \tag{12}$$

$$i_{rxy}=1-\left(\frac{d_{xy}}{d_{r\max}}\right)\text{(Linear attenuation)}\,, \tag{13}$$

$$i_{rxy}=\exp\left(\frac{-2.99d_{xy}}{d_{r\max}}\right)\text{(Exponential attenuation)}\,, \tag{14}$$

$$Q_{xj}=H_j\left[1-\left(\frac{D_{xj}^z}{D_{xj}^z+k^z}\right)\right], \tag{15}$$

where Q_{xj} is the habitat quality index of pixel x in habitat type j; D_{xj} is the habitat degradation of pixel x in habitat type j; k is the half-saturation factor, generally set to 1/2 of the maximum value of habitat degradation; z is the default parameter of the model, with a value of 2.5; H_j is the habitat suitability of habitat type j, with a value between 0 and 1; R is the number of stress factors; Y_r is the number of pixels of the stressor r; W_r is the weight of the stressor r; r_y is the stress value of pixel y; i_{rxy} is the stress level of the stressor r of pixel y on pixel x; β_x is the accessibility of the stressor r to pixel x (the degree of legal protection factor is not considered in this study, so β_x is set to 1); S_{jr} is the sensitivity of habitat type j to the stressor r; d_{xy} is the linear distance between pixel x (habitat) and pixel y (threat factor); and $d_{r\max}$ is the maximum stress distance of stress

factor r. The degree of habitat degradation ranged from 0 to 1, and the higher the value, the greater the degree of habitat degradation.

2.3.5 Analysis of comprehensive hotspots of ecosystem services

The identification of integrated hotspots of ecosystem services in the study area can provide a qualitative basis for the formulation and decision-making of local ecological conservation measures. In this study, we used ArcGIS to identify the areas where each ecosystem service exceeded its respective average value as the hotspot areas of that ecosystem service at the raster scale, and obtained the distribution of the integrated hotspot areas of ecosystem services in 2010 and 2018 by superimposing the hotspot areas of the four ecosystem services in each corresponding year. Based on the number of individual ecosystem service hotspots in the area, we classified the hotspot areas into five categories: category IV hotspot areas (all four ecosystem services exceeded the average value), category III hotspot areas (three ecosystem services exceeded the average value), category II hotspot areas (two ecosystem services exceeded the average value), category I hotspot areas (one ecosystem service exceeded the average value), and noncritical areas (none of the ecosystem services exceeded the respective average value).

3 Results

3.1 Spatiotemporal variations in ecosystem services

3.1.1 Spatiotemporal variations in soil conservation service

From the perspective of spatial distribution, the spatial differentiation characteristics of soil conservation service in 2010 and 2018 were relatively large (Fig. 2). In 2010, the amount of soil conservation in the eastern and southwestern regions was higher than that in the northwest (Fig. 2a). It was higher in the east (including Yanchuan, Yanchang, Yichuan, and Huanglong counties) and in the southwest (Huangling County), while it was lower in the north (including Wuqi and Zhidan counties, Ansai District, and Zichang City). In 2018, the amount of soil conservation in the northwest (Wuqi and Zhidan counties, Ansai District, and Zichang City) was higher than that in other regions (Fig. 2b), and the gap between the highest and the lowest amount of soil conservation showed a trend of narrowing.

From 2010 to 2018, the soil conservation service of Yan'an City showed a decreasing trend. The total amount of soil conservation of Yan'an City was 4.07×10^6 t in 2010. In 2018, the total amount of soil conservation in Yan'an City decreased to 3.75×10^6 t. That was a decrease of 7.76%. An increase of more than 5.00% in the value of soil conservation change was defined as an increasing area, a decrease of more than 5.00% was defined as a decreasing area, and a change between ±5.00% was defined as a basically unchanged area. According to the raster statistics, the area with increased soil conservation accounted for 18.12%, the area with decreased soil conservation accounted for 22.37%, and the area with no significant change accounted for 59.51% of the total area. The basic trend of the change in soil conservation was an increase in the northwest and a decrease in the southeast (Fig. 2c).

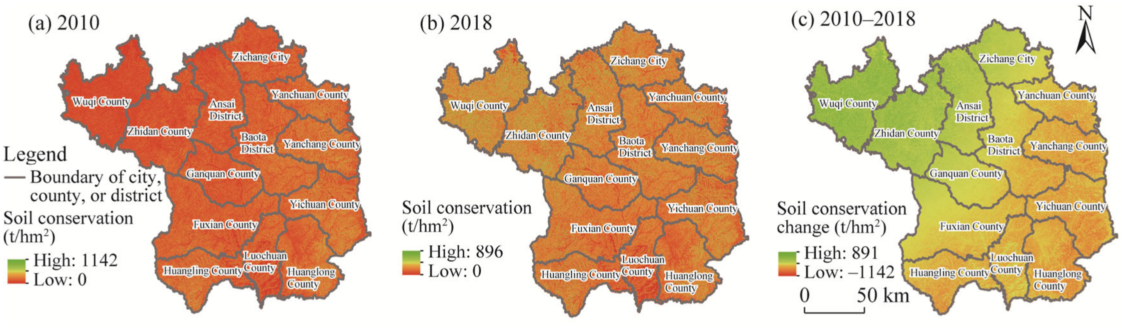

Fig. 2 Spatial distribution of soil conservation in Yan'an City in 2010 (a) and 2018 (b) and the change in soil conservation during 2010–2018 (c)

3.1.2 Spatiotemporal variations in water yield service

The spatial distribution pattern of water yield service in Yan'an City is greatly influenced by rainfall. In 2010, the amount of water yield showed a decreasing trend from south to north (Fig. 3a), which was higher in Huanglong, Huangling, and Luochuan counties and lower in Wuqi and Yanchuan counties and Zichang City. In 2018, the spatial pattern of water yield in Yan'an City underwent significant changes, showing a trend of being higher in the southwest and lower in the northeast (Fig. 3b). From 2010 to 2018, the water yield in Yan'an City showed an increasing trend. The total amount of water yield in 2010 was 2.01×10^{10} mm, with an average value of 489.52 mm per unit area, and in 2018, the total amount increased to 2.03×10^{10} mm and the average value was 492.30 mm per unit area, increasing by 0.56%. According to raster statistics, the increased area accounted for 42.19% and was mainly distributed in the north, the decreased area accounted for 50.02% and was mainly distributed in the south, and 7.79% of the area had no significant change (Fig. 3c).

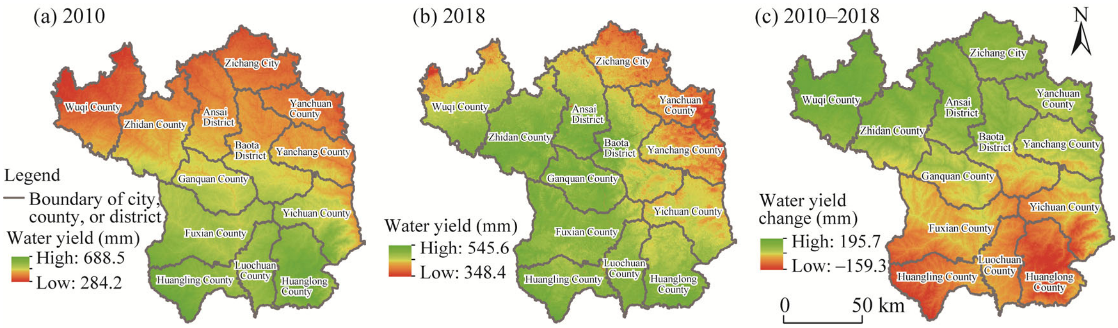

Fig. 3 Spatial distribution of water yield in Yan'an City in 2010 (a) and 2018 (b) and the change in water yield during 2010–2018 (c)

3.1.3 Spatiotemporal variations in carbon storage service

The spatial distribution of carbon storage service in Yan'an City is generally consistent with the distribution of land use types. Specifically, the southwestern and southeastern parts of the city had a stronger carbon storage capacity due to more forestland, while the northern parts, especially the northern parts of Ansai District, Zichang City, and Baota District, had a large amount of cultivated land, so the carbon storage capacity is relatively weaker (Fig. 4a–b). Carbon storage was relatively stable from 2010 to 2018. In 2010, the total amount of carbon storage in Yan'an City was 3.80×10^8 t, and the average carbon density was 102.18 t/hm^2. In 2018, the total amount of carbon storage and average carbon density were 3.79×10^8 t and 102.02 t/hm^2, respectively, with carbon storage decreasing by 0.16% during 2010–2018. According to the raster statistics, carbon storage increased in 3.00%, decreased in 3.30%, and did not change significantly in 93.70% of the total area. The region with the most significant change was Baota District, which basically coincides with the urban expansion area, where the carbon storage capacity was weakened and the carbon stock loss was due to the gradual increase in construction land in the urban center (Fig. 4c).

3.1.4 Spatiotemporal variations in habitat quality service

The spatial distribution of habitat quality service in Yan'an City is similar to the amount of carbon storage. The regions with a wide distribution of forestland, such as Huangling, Huanglong, Yichuan, and Fuxian counties, have better natural conditions, high forest and grass cover, high habitat suitability, and numerous nature reserves, so the habitat quality is generally high. The northern part of Yan'an City has low precipitation and poor natural environment and vegetation cover, and is the main low-value area of habitat quality. Although Luochuan County has better natural conditions, the valley, with lower elevation, has better cultivation conditions, and the habitat quality is more susceptible to human interference so it is also poor (Fig. 5a–b). In 2010

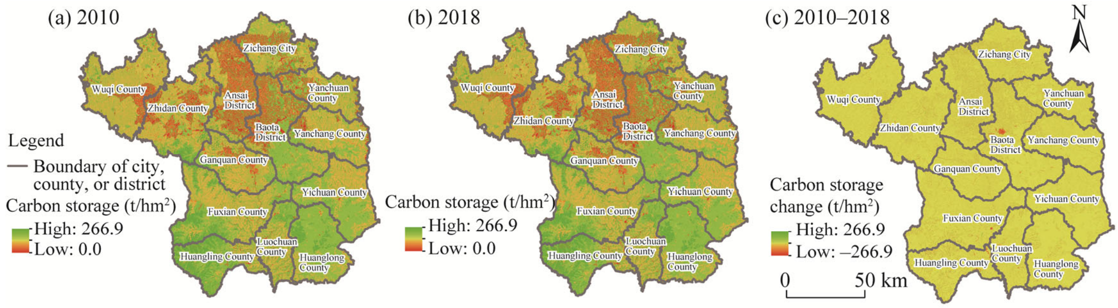

Fig. 4 Spatial distribution of carbon storage in Yan'an City in 2010 (a) and 2018 (b) and the change in carbon storage during 2010–2018 (c)

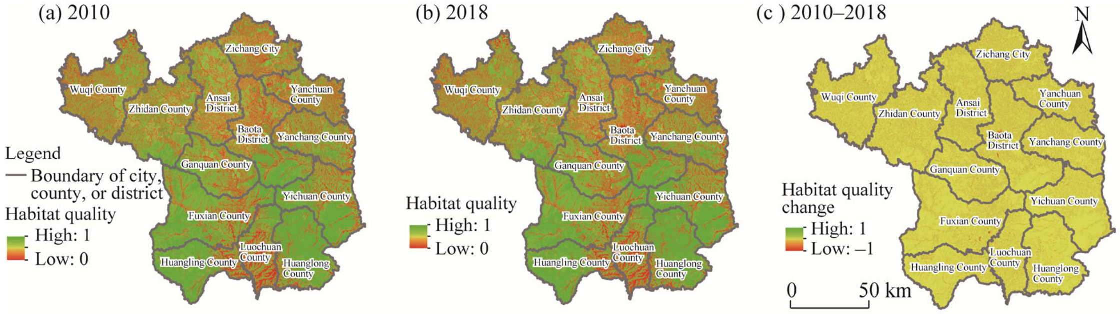

Fig. 5 Spatial distribution of habitat quality in Yan'an City in 2010 (a) and 2018 (b) and the change in habitat quality during 2010–2018 (c)

and 2018, the average values of habitat quality in Yan'an City were 0.5914 and 0.5906, respectively, and the habitat conditions were at a medium level. The habitat quality decreased by 0.14% during 2010–2018. From 2010 to 2018, the region with increased habitat quality accounted for 5.42%, the region with decreased habitat quality accounted for 5.52%, and the central part of Baota District experienced a significant decrease. The remaining 89.06% of the area had relatively stable values without significant changes (Fig. 5c).

3.2 Hotspots and trade-off and synergy analysis of ecosystem services

3.2.1 Spatial heterogeneity of ecosystem service hotspots

The distribution of the integrated hotspot areas of ecosystem services in Yan'an City is shown in Figure 6. In 2010, the four types of hotspot areas were ranked as follows: category IV hotspot areas>category III hotspot areas>category II hotspot areas>category I hotspot areas, with area proportions of 31.83%, 31.78%, 22.94%, and 13.24%, respectively. In 2018, the four types of hotspot areas were ranked as follows: category III hotspot areas>category II hotspot areas>category IV hotspot areas>category I hotspot areas, with area proportions of 43.43%, 29.73%, 19.20%, and 7.57%, respectively. Category II and category III hotspot areas increased by 6.79% and 11.60%, respectively, while category I and category IV hotspot areas decreased by 5.67% and 12.63%, respectively. The percentage of noncritical areas was small, only 0.21% in 2010 and 0.07% in 2018.

From the spatial distribution and hotspot areas of ecosystem services in each region of Yan'an City, it can be seen that hotspot areas in southern Yan'an City were significantly higher than that in northern Yan'an City in 2010. The category IV hotspot areas were mainly distributed in Huangling and Huanglong counties in the southwest and southeast of Yan'an City. There are more mountainous areas in this part of the city, and the water, heat, and vegetation conditions are better than those in other areas. Category III hotspot areas were distributed in the periphery of category IV hotspot areas, outside Huanglong and Huangling counties, and in Yichuan, Luochuan, Fuxian, and Ganquan counties in central and southern Yan'an City. Category II hotspot areas were mainly

distributed in Ganquan, Luochuan, Yanchuan, and Yanchang counties of Yan'an City. Category I hotspot areas were mainly distributed in Wuqi and Zhidan counties, Ansai District, and Zichang City of Yan'an City. This area generally has a high altitude and arid climate, the environmental conditions are more severe, and the temperature and precipitation conditions are worse than those in the southern part. In 2018, the hotspot areas in Zhidan and Wuqi counties, Ansai District, and parts of Baota District increased significantly, changing from category I hotspot areas to category II or III hotspot areas, while the hotspot areas in the southeast changed from category IV hotspot areas to category II or III hotspot areas. The changes in ecosystem service hotspot areas indicate that the ecological environment of the study area is developing towards equilibrium.

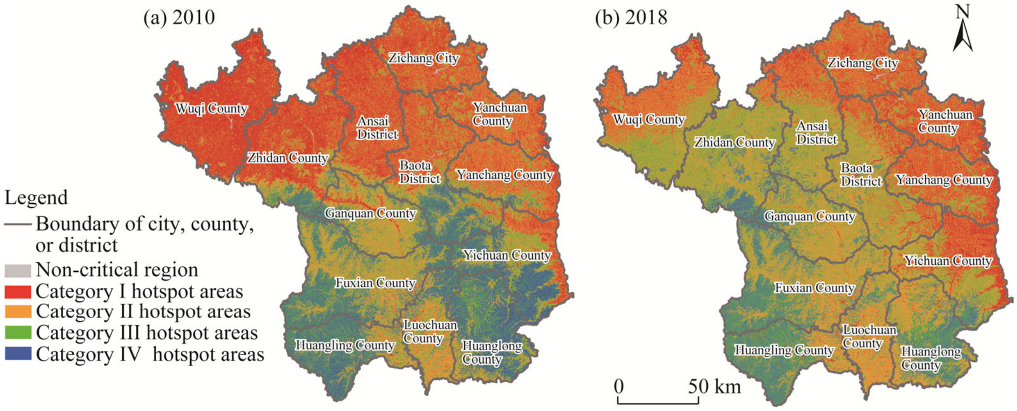

Fig. 6 Comprehensive hotspot areas of ecosystem services in Yan'an City in 2010 (a) and 2018 (b)

3.2.2 Ecosystem services trade-off and synergy analysis

To further explore the trade-offs and synergistic relationships among ecosystem services in Yan'an City, we calculated the ecosystem service changes of each region during 2010–2018 to identify the interrelationships among soil conservation service, water yield service, carbon storage service, and habitat quality service. As shown in Table 2, the four ecosystem services were positively correlated, showing a synergistic relationship of mutual gain. The synergistic relationships between soil conservation service and water yield service and between carbon storage service and habitat quality service were extremely significant (*P*<0.01), while the synergistic relationships between other ecosystem services were weak.

Table 2 Correlation coefficients among ecosystem services

Ecosystem service	Soil conservation service	Water yield service	Carbon storage service	Habitat quality service
Soil conservation service	1.000			
Water yield service	0.786^{**}	1.000		
Carbon storage service	0.301	0.327	1.000	
Habitat quality service	0.164	0.310	0.722^{**}	1.000

Note: ** indicates a significant correlation at *P*<0.01 level.

3.3 Correlation analysis between the implementation data of the GCLC project and the change in ecosystem services

Based on the Pearson correlation coefficient, we used SPSS18.0 software to analyse the correlation between the implementation data of the GCLC project (including the number of projects, construction scale, newly increased cultivated land, high-standard farmland, and investment amount) in 13 regions of Yan'an City (Table 1) and the change in ecosystem services. The results showed that from 2010 to 2018, there was a positive correlation between the

implementation data of the GCLC project and the change in water yield service and a negative correlation between the implementation data of the GCLC project and the change in carbon storage service and habitat quality service in different regions (Table 3). Additionally, the construction scale, newly increased cultivated land, high-standard farmland, and investment amount were significantly negatively correlated with the change in carbon storage service (P<0.05). There was no significant correlation between the implementation data of the GCLC project and the change in other ecosystem services. The correlation analysis indicates that the GCLC project has some negative effects on ecosystem services. With anthropogenic disturbance and land use changes, the value of ecosystem services inevitably decreases. However, the impact of the GCLC project on soil conservation service, water yield service, and habitat quality service in Yan'an City was not significant.

Table 3 Correlation between the implementation data of the GCLC project and the change in ecosystem services

	Number of projects	Construction scale	Newly increased cultivated land	High-standard farmland	Investment amount
Soil conservation service	0.033	–0.066	0.030	–0.157	–0.083
Water yield service	0.316	0.295	0.475	0.204	0.289
Carbon storage service	–0.525	–0.602*	–0.590*	–0.599*	–0.609*
Habitat quality service	–0.390	–0.476	–0.221	–0.533	–0.487

Note: * indicates a significant correlation at P<0.05 level.

4 Discussion

4.1 Change in ecosystem services in Yan'an City

Except for soil conservation service, the ecosystem services in Yan'an City maintained a relatively stable dynamic change from 2010 to 2018. The changes in the other three ecosystem services (water yield service, carbon storage service, and habitat quality service) were all less than 1.00%. After the GFG project was implemented in 1999, the total value of ecosystem services on the Loess Plateau increased significantly (Zhang et al., 2016), and its change was closely related to the change of cultivated land to forestland and grassland (Liu and Wang, 2018; Hou et al., 2019). However, the transfer of cultivated land to forestland, grassland, and construction land has reduced the value of some ecological services (Xiong and Shi, 2018). The study shows that the cultivated land area in Yan'an City decreased at an average annual rate of 10.00%, and the food production capacity decreased by 16.00% (Xie et al., 2020). With the development of the social economy and the growth of the population, the conflict between humans and land is increasing, and the insufficient food production is likely to threaten the achievements of the GFG project. Since 2010, the GFG project has entered the consolidation stage, and the implementation intensity is lower than that of the previous period. At the same time, the GCLC project began to be carried out on a large scale, which achieved better coordination between agricultural and ecological land in this period, ensuring the balance of various land resources in Yan'an City, and maintained the ecosystem services in a relatively stable state.

4.2 Ecosystem services trade-off and synergy in Yan'an City

The study found that all four ecosystem services in Yan'an City exhibit synergistic relationships of mutual gains, which is consistent with the research results of Wang et al. (2019) on the Loess Plateau. Generally, there is a synergistic relationship between the two regulatory services (soil conservation service and carbon storage service) and between support services (habitat quality service) and regulatory services (Jia et al., 2014), while the trade-off relationship between regulatory services and supply services (water yield service) is inconsistent. For example, there is usually a trade-off relationship between food supply and other ecosystem services (Yang et al., 2022). However, water yield service has a synergistic relationship with soil conservation service

and a trade-off relationship with net primary productivity (Wang et al., 2022). Due to a variety of conditions, such as climate, topography, and land use, the trade-off relationship among ecosystem services shows spatial heterogeneity and temporal dynamics and changes with spatial and temporal scales (Su and Fu, 2013). At the urban scale, both soil conservation service and water yield service are mainly affected by rainfall, so they exhibit a relatively significant synergy, while the changes in carbon storage service and habitat quality service are consistent with land use change, and the synergy between them is also significant.

4.3 Impact of the GCLC project on changes in ecosystem services

The results show that the GCLC project has a negative impact on the ecosystem services in Yan'an City, but it is only significantly related to carbon storage service. On the one hand, land consolidation exerts a direct impact on crop production, climate regulation, and other ecosystem services through engineering measures. On the other hand, it indirectly changes regional ecosystem services and their distribution pattern and functions through the reorganization and redistribution of land resources and their utilization patterns (Zhong and Wang, 2017). Most studies have shown that land consolidation improves ecosystem food production services while weakening other services and the total values (Zhao et al., 2004; Kindu et al., 2016). Cultivated land is one of the emission sources of CO_2, CH_4, N_2O, and other greenhouse gases (Firbank et al., 2013). Therefore, in this study, the GCLC project has a significant negative impact on carbon storage service. Although land disturbance and habitat fragmentation during implementation have a negative impact on regional ecosystem services, they have a positive impact on some regional ecosystem services through scientific optimization of land use patterns and structure, such as field integration, water resource regulation, improvement of farmland infrastructure and agricultural production conditions, reasonable adjustment of planting structure, and other measures. Studies have shown that land consolidation has a positive impact on habitat quality, nutrient storage and recycling, and other support services as well as cultural services. Moreover, comprehensive ecological land consolidation technology can promote the synergistic improvement of various ecosystem services after land consolidation (Wang et al., 2018).

4.4 Suggestions

Economic benefit is an important component of land ecological quality. Economic growth can promote industrial development and upgrading, thus improving regional ecological efficiency and helping to protect the regional ecological environment (Ren and Du, 2021). Regional development must not only pursue the improvement of a single ecosystem service but also balance the multiple goals of ecological protection, food security, and economic development. If economic development is sacrificed in ecological protection, it will also lead to an irrational industrial structure and low ecological efficiency. It can be seen from the implementation scale of the GCLC project and the distribution of ecosystem services that each region in Yan'an City plays different roles in ecological protection, food security, and economic development due to different natural conditions and habitat characteristics, and the implementation focus of the GCLC project and its impact on the change in ecosystem services are also different. The results of this study show that during 2010–2018, according to the environmental characteristics and ecological economic functions of different regions, the government of Yan'an City carried out targeted development and protection. Through changes in land use patterns and the rational allocation of various types of land, environmental deterioration caused by economic development can be prevented while ensuring the stability of various ecosystem service functions. This effectively alleviates the current situation of the drastic decline in cultivated land area and insufficient food production capacity in this region, balances the conflict between ecological protection and farmers' livelihoods, realizes the coordinated development between ecological security and food security as well as quality development and ecological protection, and promotes the optimal balance of ecology, economy, and society in Yan'an City.

In the future, researchers and policymakers should formulate corresponding strategies

according to local conditions to realize the coordination and optimization of the regional ecosystem services. For example, Huangling and Huanglong counties should strengthen ecological and environmental protection in ecological red line area. In the eastern potential area of agricultural production, the GCLC project should be carried out to improve the quality of cultivated land and prevent the environmental degradation caused by economic development. In the northern part, it is suggested to rationally plan the implementation of the GCLC project and human activities, improve the level of agricultural infrastructure, maintain the achievements of ecological restoration, and make every effort to ensure and improve people's livelihoods.

5 Conclusions

From 2010 to 2018, except for the decline in soil conservation service, the changes in the other three ecosystem services were relatively stable. Soil conservation decreased by 7.76%, increasing in the northwest and decreasing in the southeast. The water yield increased by 0.56%, with a basic trend of increasing in the north and decreasing in the south. The carbon storage and habitat quality decreased by 0.16% and 0.14%, respectively, with the most significant decrease observed in the urban expansion area. The area of hotspots in southern Yan'an City is higher than that in northern Yan'an City. From 2010 to 2018, category II and category III hotspot areas increased, while category I and category IV hotspot areas decreased, indicating that the ecological environment of the study area was developing in a balanced way. The four ecosystem services in Yan'an City showed synergistic relationships, among which soil conservation service and water yield service as well as carbon storage service and habitat quality service had significant synergistic relationships. There was a positive correlation between the implementation data of the GCLC project and the change in water yield service and a negative correlation between the implementation data of the GCLC project and the change in carbon storage service and habitat quality service in different regions of Yan'an City. There were differences in the implementation focus of the GCLC project and its impact on the change in ecosystem services among different regions in Yan'an City. In the future, researchers and policymakers should formulate corresponding strategies according to local conditions to realize the coordination and optimization of regional ecosystem services.

Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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